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Capt. Hilda Jane Snelling USAF for the M.S. in Meteorology

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Title Production Efficiency of Different [illegible]

Ice-Forming Nuclei Generators

Abstract approved Fred W. Decker

Tests compared the production efficiencies of the following three silver iodide ice-forming nuclei generators: one burning charcoal soaked in a 2% silver iodide acetone solution, one in which a jet of propane gas atomized a 2% silver iodide acetone solution, and one in which a jet of compressed air atomized this same solution.

An optical pyrometer measured the generator operating temperatures. The United States Weather Bureau Bigg-Warner Type Ice Nuclei Counter provided counts of the number of effective ice nuclei produced by the generators at different temperatures. The tests occurred at these three temperatures of the ice nuclei counter, -12°C, -15°C, and -20°C.

The number of active nuclei produced per second of operation and the number of active nuclei produced per gram of silver iodide used determined the efficiency of the generator. In all cases tested the acetone air generator had higher efficiency than either the charcoal generator or the propane generator. Both the acetone air generator and the propane generator had equal efficiency at the two operating temperatures tested.

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(6) PRODUCTION EFFICIENCY OF DIFFERENT SILVER IODIDE ICE-FORMING NUCLEI GENERATORS,

(1) by

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PRODUCTION EFFICIENCY OF DIFFERENT SILVER IODIDE ICE-FORMING NUCLEI GENERATORS

I. INTRODUCTION

Attempts at cloud modification using silver iodide have involved several different types of generators for producing ice-forming nuclei. Various investigators have made studies of the efficiency of these generators. The number of nuclei produced per gram of silver iodide dispersed into a cloud of a given temperature and the number of nuclei produced per second of generator operation provide the criteria which determine the production efficiency of the generator. The major types of generators either burn an acetone solution of silver iodide atomized by a combustible gas or air, or burn a string or solid fuel such as charcoal soaked in the silver iodide acetone solution.

Researchers have studied several factors influencing the efficiency of the generators. Dessens (3, p.23-40) and Soulage (12, p.1-8) found an acetone solution containing 1½ to 2% silver iodide by weight the most efficient solution. Smith, Hefferman, and Seely (10, p.379) studied the decay of the ice-nucleating properties of silver iodide for different generators. For a hydrogen generator the number of effective ice-forming nuclei decreased by a factor of ten after eight minutes exposure in the free atmosphere. The nuclei

from a kerosene generator required fifty minutes for the same amount of decrease. Vonnegut (15, p.595) and Fletcher (4, p.385-387) studied the effect of the size of silver iodide particles. Vonnegut found the oxyhydrogen flame generator produced particles with a diameter of 100 Angstroms which became effective as ice-forming nuclei at temperatures colder than -7°C. When a hot wire vaporized the silver iodide giving particles of one micron diameter the effective temperature rose to -4°C. Fletcher found that in one second a particle with a diameter of 100 Angstroms would nucleate an ice crystal at a temperature -40°C. A 1000 Angstrom particle required a temperature of only -10°C, and a micron particle required only a -5°C temperature.

The dispersal temperature of the silver iodide influences the efficiency of the generator. Investigators have found somewhat conflicting results in their studies of this factor. Dessens (3, p.23-40), who has made the most comprehensive study, found the highest efficiency in a generator burning the acetone silver iodide solution in air at a comparatively low temperature, 750°C, in the case of the generator of L'Association d'Etudes des Moyens de Lutte Contre les Fléaux Atmosphériques. Fuquay (13, p.275) in his studies of the Skyfire Generator, which burns the acetone silver iodide solution in a propane gas flame, stated that the output increased linearly from 400°F to 2000°F (982°C). The latter temperature appeared the most efficient operating temperature for all the generators tested, including the Skyfire Generator, another type of propane flame acetone burning generator, and two models of generators burning a silver iodide acetone soaked string. Krick (8, p.1250-1263) did not relate

temperature to efficiency but did state that his coke burning generators operate at a temperature of 2500°F. Soulage (12, p.1-8) made no mention of operating temperature in his study of charcoal burning generators. Balabanova, Maleev, and Zhigalovskaya (2, p.941-944) studied the extent of destruction of the silver iodide particles at three temperatures. The exposure of the particles lasted 30 minutes at 650°C, 5 minutes at 900°C and 1.5 minutes at 3000°C. They found that the mean values for the destruction at these temperatures were respectively 3.09%, 2.97%, and 4.69%.

Researchers have used different methods in testing the various generators. Dessens (3, p.23-40), Vonnegut, (16, p.277-289), and Fuquay (5, p.79-91; 13, p.274) used a wind tunnel for measuring the rate of flow from the generator and a cold box for counting the number of ice crystals in a sample taken from the wind tunnel. Soulage (12, p.1-8) completely burned small bits of his charcoal, so he knew the total weight of the silver iodide dispersed in a given period of time. He also described a method of operating a generator in a closed room and withdrawing a small volume of the air and then counting the ice crystals formed by means of a special cold chamber (11, p.81-90).

Faced with these somewhat conflicting results of studies of operating temperatures, differing methods of testing the generators, and the great variety of generators, I decided to test three major types of generators at as many different operating temperatures of the generators as feasible, to use a simple vertical wind tunnel for measuring the volume of output, and to count the number of nuclei

by using the U. S. Weather Bureau Bigg-Warner Type Ice Nuclei Counter. In the pages to follow I will set forth the equipment used, the methods of collecting and analyzing the data, the conclusions, and suggestions for further research.

II. DESCRIPTION OF EQUIPMENT USED

The three types of generators under test included one burning charcoal impregnated by a 2% silver iodide acetone solution, one burning a 2% silver iodide acetone solution in a propane flame, and one in which a jet of compressed air atomized the 2% silver iodide acetone solution and the acetone furnished the necessary substance for combustion. In the absence of commercial silver iodide generators of each type, I had suitable equipment designed and fashioned. I decided not to test the type of generator which burns a string soaked in the silver iodide acetone solution since Fuquay (5, p.79-91) described tests of this type generator and had found the propane flame Skyfire Generator more efficient.

Fuquay in the Final Report of the Advisory Committee on Weather Control (13, p.275-280) set forth the details of the construction of the Skyfire Generator. Plate I shows my slightly modified version of this generator. The propane orifice has a 0.029 inch diameter. The generator has a 22 gauge hypodermic needle with the slant ground off mounted 3/16 of an inch above the propane orifice. The jet of propane gas nebulizes the acetone solution drawn from the reservoir through the hypodermic needle. A 100 milliliter graduate served as the reservoir for the silver iodide acetone solution. This permitted an easy reading of the amount of solution used during any operating

PLATE I

DETAIL OF PROPANE GENERATOR

period of the generator. A regulator on the propane tank made it possible to vary the pressure of the gas by half pound values from zero to thirty pounds per square inch. Three inch iron pipe formed the flame chamber. Plate II shows the complete layout of the apparatus.

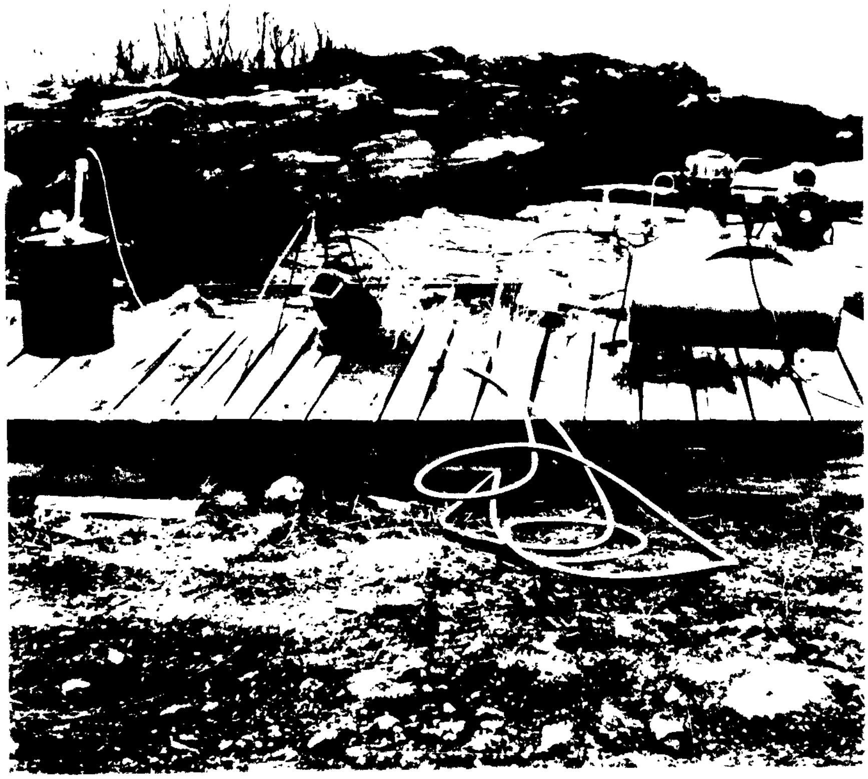
Having procured this generator, I used it as the acetone air generator by substituting compressed air for the propane gas. A gauge and regulator on a commercial compressor permitted regulation of the pressure to half pound values in a range from zero to forty pounds per square inch. Plate III shows the compressor and layout of the apparatus. The acetone did not burn readily, but changing the hypodermic needle to a larger one of gauge 16 eliminated most of the difficulty.

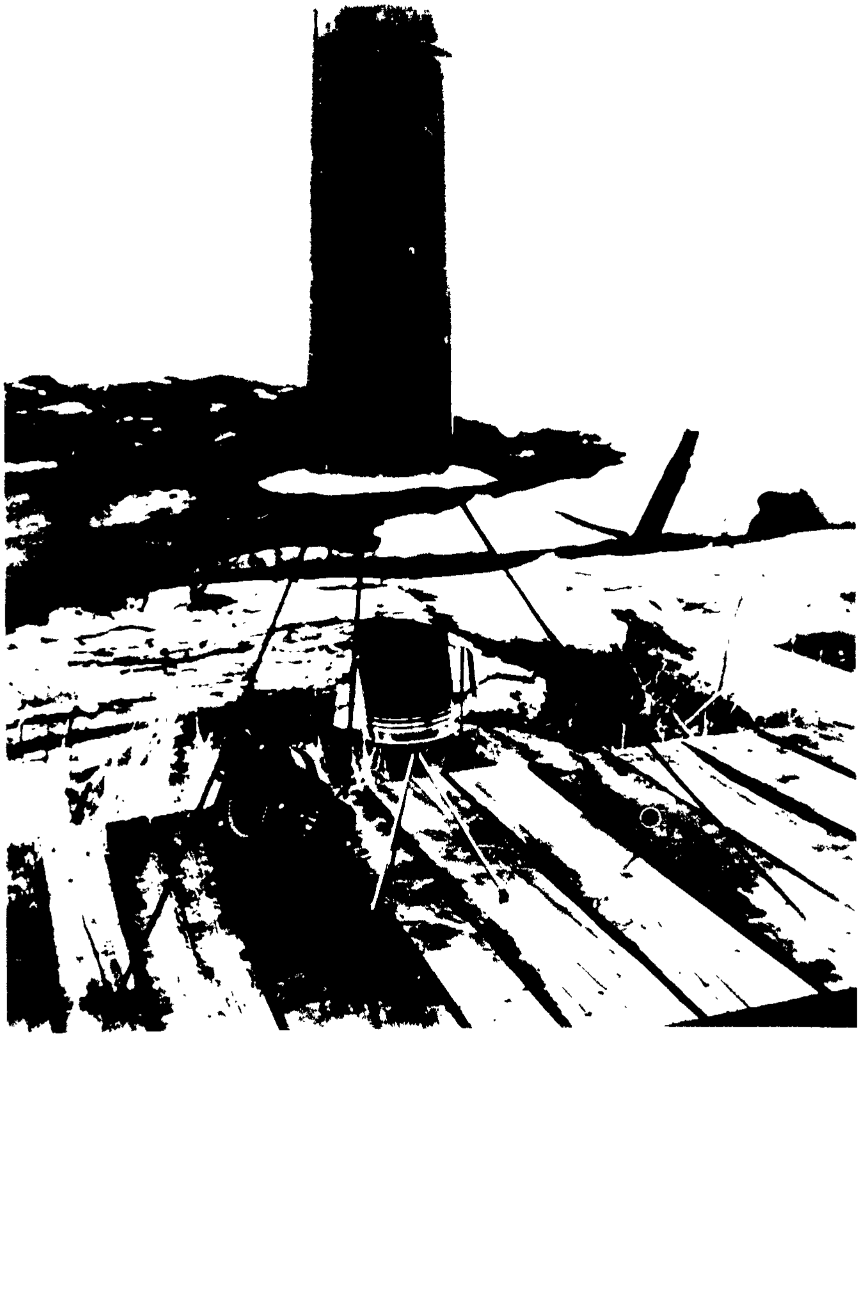
The construction of the charcoal generator involved simply removing the handle and revolving bands from a small flour sifter and placing this sifter on a flowerpot stand. An electric fan under the stand furnished enough ventilation to keep ash from forming on the charcoal and forced the generator output upward through the wind tunnel. The wind tunnel consisted of a two foot length of eight inch diameter stovepipe with metal rods for legs. Plate IV shows this setup. I used a ten cubic centimeter veterinary syringe to obtain a sample of the generator output from the top of the wind tunnel, dilute the sample, and then inject it into the nuclei counter. An anemometer held over the top of the stovepipe measured the rate of flow through this wind tunnel.

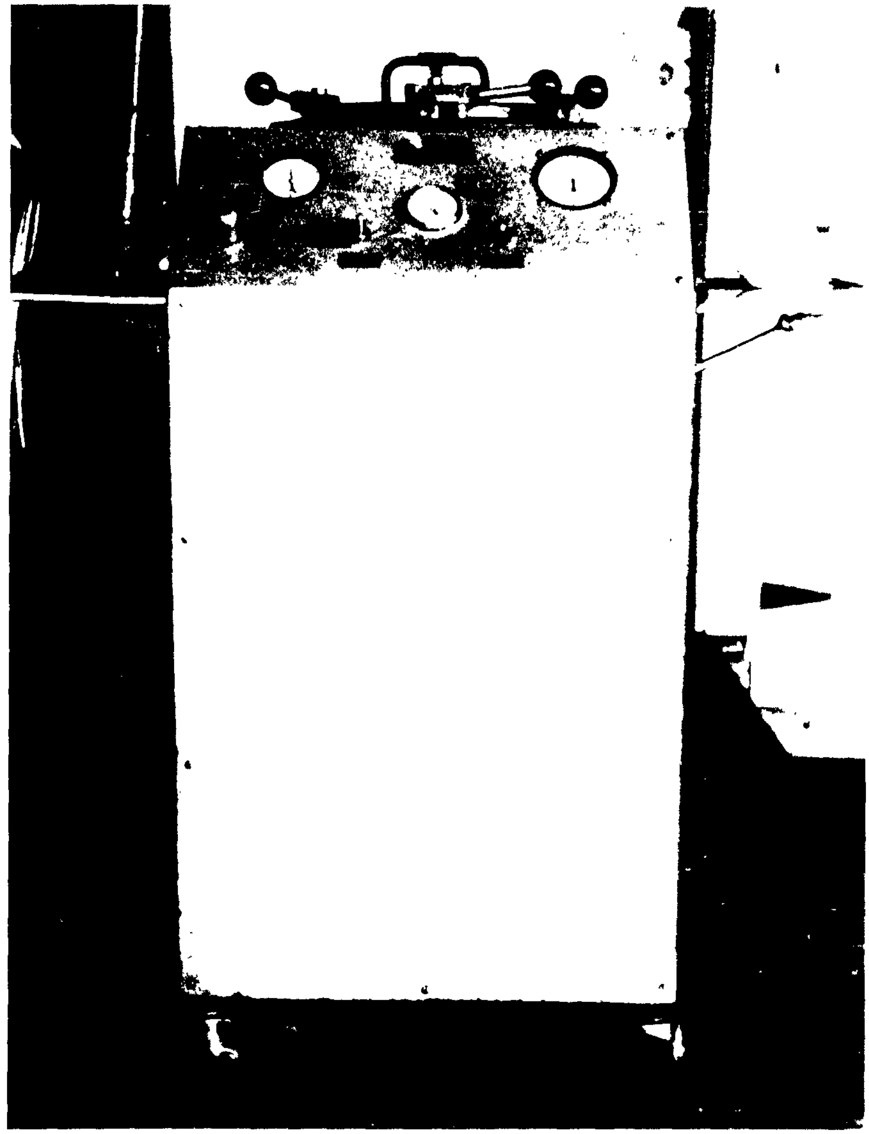
The United States Weather Bureau Bigg-Warner Type Ice Nuclei Counter available for use in this project appears in Plate V. This

PLATE II

PROPANE GENERATOR WITH ACETONE RESERVOIR, PROPANE TANK, WIND TUNNEL, AND ELECTRIC FAN







counter consists of a ten liter insulated copper chamber pressurized to any desired pressure with the wall temperature refrigerated to any desired temperature. After cooling the air sample to wall temperature, opening a release valve suddenly decompresses the chamber to produce a supercooled fog. The ice crystals which form settle into a removable tray which contains a thin layer of sugar solution. Crystals then grow to sufficient size for counting by visual inspection. Plates VI and VII show trays containing a small and a very large number of ice crystals respectively. The most effective concentration of the sugar solution varies with the temperature and Admirat (1, p.133-140) has determined the most effective concentrations for a wide range of temperatures.

In order to study the operating temperatures of the generators, a Leeds Northrup Optical Pyrometer provided indications of the temperature of the flame at the top of the flame chamber in the propane and acetone air generators and of the burning charcoal in the charcoal generator.

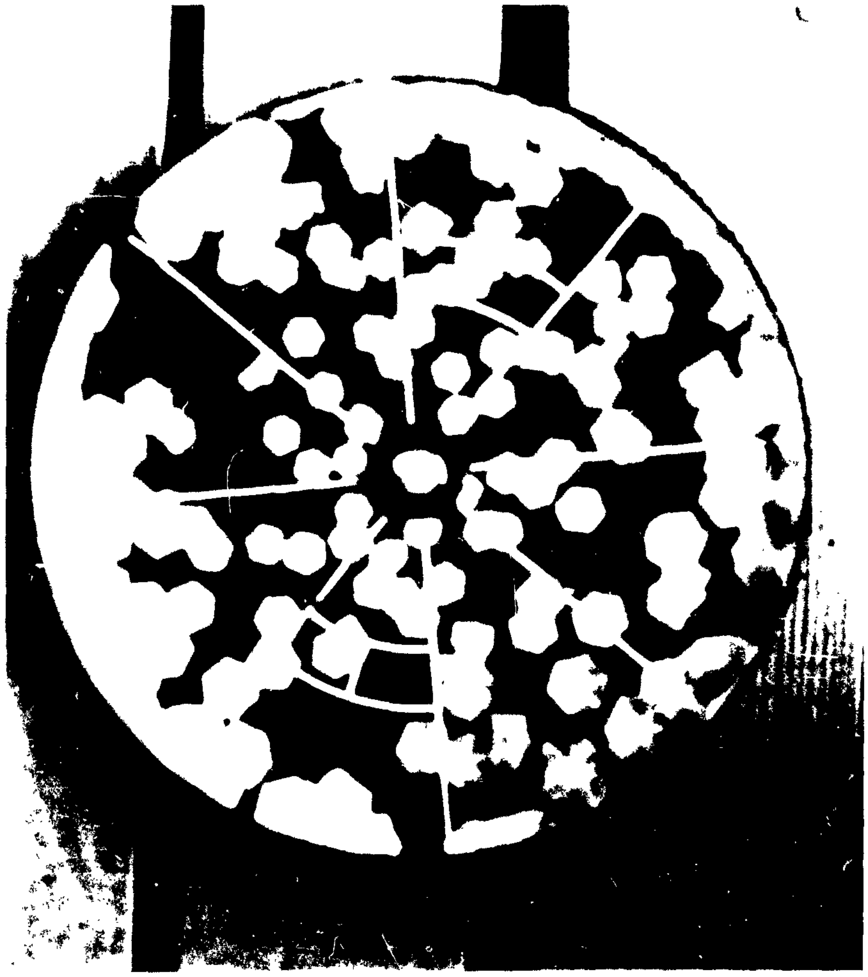


PLATE VI

TRAY WITH A SMALL NUMBER OF ICE CRYSTALS

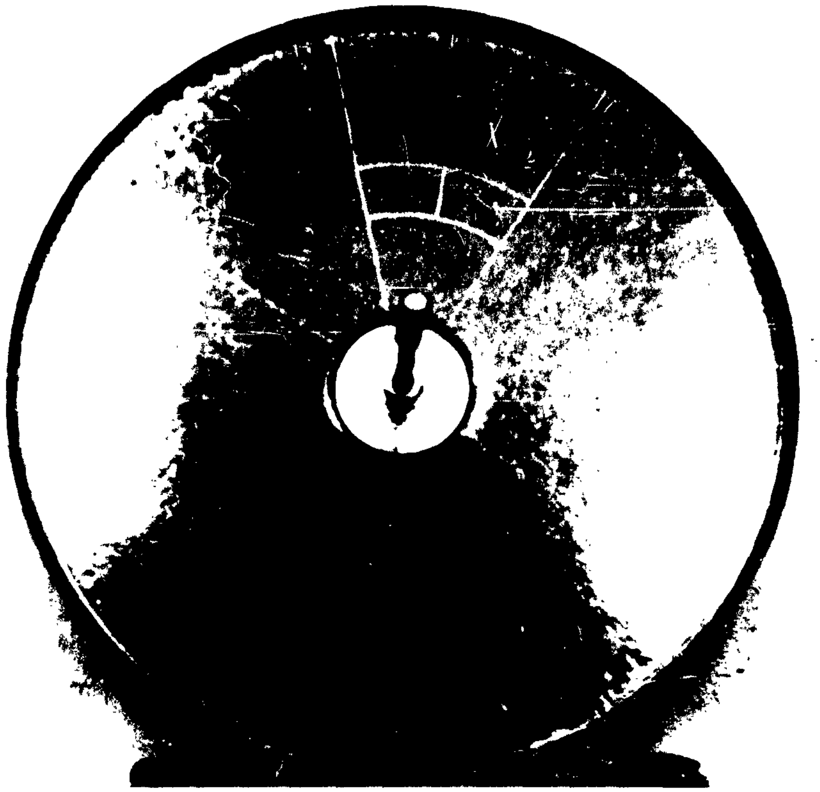


PLATE VII

TRAY WITH A VERY LARGE NUMBER OF ICE CRYSTALS

III. COLLECTION AND ANALYSIS OF DATA

The optical pyrometer furnished the solution to the problem of determining the operating temperatures of the generators and the range of possible temperature variations in each generator. Since the optical pyrometer measures the black body temperature, all reported temperatures contain a correction factor determined from tables (6, p.186). When testing the charcoal generator the optical pyrometer showed a corrected temperature of approximately 2050°F. There appeared no feasible method of varying the operating temperature of the charcoal generator.

In conducting temperature tests of the acetone air and propane generators at various pressures of the gases, the only detectable changes occurred in the range of pressure values from one to five pounds per square inch. The operating temperatures averaged 1630°F for propane at 1 psi, 1730°F for propane at 5 psi, 1450°F for air at 1 psi, and 1580°F for air at 5psi.

In selecting the testing temperatures of the supercooled fog in the ice nuclei counter the criteria required a temperature as warm as feasible, a temperature of -20°C since other researchers have generally stated the efficiency of their generators in terms of this temperature, and an intermediate value. I hoped to use -10°C as the warmest temperature but in tests with the nuclei

counter the length of time required for a count at this temperature and the greater risk of contamination of the count made it more feasible to use -12°C as the warmest temperature. A temperature of -15°C fulfilled the requirement for the third value.

With the nuclei counter located there and a low risk of contamination the Oregon State University radar site on the summit of McCulloch Peak proved a good location for the testing of the generators. The normal variability of the natural nuclei count required conducting tests on several days. Checks of the natural nuclei counts on these days showed no crystals at -15°C and -12°C and only 20 to 100 at -20°C. This proved such a small fraction of the counts observed in the samples from the generators that I did not include corrections for the natural count in the analysis. The use of a random number table to determine the testing order of the generators also served to eliminate effects due to variations in the natural count.

Plates II and IV show the relative positions of the generator, the electric fan, and the wind tunnel but not their location downwind from the nuclei counter. An anemometer measured the prevailing wind speed and the rate of flow through the tunnel for each generator. Figure 1 shows a sample of the data recorded for each test of a generator and the computed efficiency.

After withdrawing a ten cubic centimeter sample from the top of the wind tunnel with the syringe, diluting the sample the desired amount by moving the plunger back and forth in the clean air upwind from the generator, and injecting a portion of the diluted sample into

Figure 1

Date: March 18, 1963 Location: McCulloch Peak

Generator: Acetone Air Temperature of Generator: 1450°F

Pressure of gas: 1 lb.

Rate of flow in wind tunnel: 405 ft./min.

Amount of AgI solution - Begin: 80 End: 10 Milliliters used: 70

Time began: 0930 Time ended: 0937 Time operated: 7 min.

Amount of smoke withdrawn: 10cc Amount of smoke injected: 1cc

Dilution factor: 3.23×10^9

#	Wall T.	Delta T.	Total T.	# crystals	#/sec	#/gram AgI
1	-9	-11	-20	300	3200×10^{10}	$10{,}000 \times 10^{12}$
2	-9	-6	-15	104	1128×10^{10}	4000×10^{12}
3	-9	-3	-12	7	76×10^{10}	240×10^{12}

Surface observation: Wind S 600 ft. per min.

Dilution Factor Computation

The dilution factor equals dilution in sampling from wind tunnel times dilution in syringe times dilution in nuclei counter.

Dilution in wind tunnel =

$$\frac{\text{vol. of tunnel}}{\text{size of sample}} \times \frac{\text{rate of flow}}{\text{length of tunnel}} \times \text{time required to take sample}$$

Hence, for the data above we have

$$\text{dilution factor} = \frac{1.9 \times 10^4 \text{cm}^3}{10\text{cm}^3} \times \frac{6.8\text{ft/sec}}{2\text{ ft}} \times \underline{1\text{ sec}} \times \frac{50\text{cm}^3}{1\text{cm}^3} \times \frac{10^4\text{cm}^3}{1\text{cm}^3}$$

$$= 1.9 \times 10^3 \times 3.4 \times 50 \times 10^4 = 3.23 \times 10^9$$

counter the length of time required for a count at this temperature and the greater risk of contamination of the count made it more feasible to use -12°C as the warmest temperature. A temperature of -15°C fulfilled the requirement for the third value.

With the nuclei counter located there and a low risk of contamination the Oregon State University radar site on the summit of McCulloch Peak proved a good location for the testing of the generators. The normal variability of the natural nuclei count required conducting tests on several days. Checks of the natural nuclei counts on these days showed no crystals at -15°C and -12°C and only 20 to 100 at -20°C. This proved such a small fraction of the counts observed in the samples from the generators that I did not include corrections for the natural count in the analysis. The use of a random number table to determine the testing order of the generators also served to eliminate effects due to variations in the natural count.

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After withdrawing a ten cubic centimeter sample from the top of the wind tunnel with the syringe, diluting the sample the desired amount by moving the plunger back and forth in the clean air upwind from the generator, and injecting a portion of the diluted sample into

the weight of silver iodide used. For the acetone air generator and the propane generator the product of the amount of solution used and the weight of silver iodide per milliliter of solution furnished the required weight.

The two tables on the following pages show the calculated values of the number of active nuclei per gram of silver iodide consumed and per second of operation for each of the generators at each of the three temperatures of the nuclei counter. Figures 2 and 3 show the graphs of the average values of these quantities for the different generators. For comparison Figure 2 also shows the maximum theoretical value which Fletcher (4, p.386) computed. Figure 4 shows values which Dessens (3, p.23-40), Fuquay (5, p.79-81), and Soulage (12, p.1-8) determined from their studies of generator efficiency.

The statistical analysis used the method of individual degrees of freedom to test various hypotheses. The use of the square roots of the numbers from Tables 1 and 2 rather than the numbers themselves offset unequal population variances. I had set up a factorial experiment and thus analyzed the data as such for both the number of active nuclei per gram of silver iodide and the number of active nuclei per second of operation. The use of a 5% significance level in all analyses means that for any given comparison there existed only a 5% risk of declaring an effect real when not.

The listing of the hypotheses for testing occurred prior to the actual tests of the generators. The first hypothesis tested whether the average output of the acetone air generator equaled the average output of the propane generator. The second tested whether the

TABLE 1

NUMBER OF ICE NUCLEI PRODUCED PER GRAM OF SILVER IODIDE

(all values have been divided by 10^{12})

Type of Generator

	Charcoal 2050°F	Propane 1630°F	Propane 1730°F	Acetone Air 1450°F	Acetone Air 1580°F
Temperature of Nuclei Counter -12°C					
	50	124	130	240	170
	43	119	50	125	420
	44	112	300	375	335
	35	140	170	170	300
	65	510	130	610	250
Total	237	1005	780	1520	1475
Mean	47.7	201.0	156.0	304.0	295.0
Temperature of Nuclei Counter -15°C					
	70	2100	1500	4000	1530
	170	2800	2500	1000	2560
	180	220	330	2500	1750
	140	80	250	1500	1000
	135	460	50	550	1230
Total	695	5660	4630	9550	8070
Mean	139	1132	926	1910	1614
Temperature of Nuclei Counter -20°C					
	1300	2700	2900	10000	7100
	1070	7100	5700	1250	5600
	1400	3020	3400	5000	2550
	750	2780	1300	5700	6570
	550	2550	2550	5100	3950
Total	5070	18150	15850	27050	25770
Mean	1014	3630	3170	5410	5154

TABLE 2

NUMBER OF ICE NUCLEI PRODUCED PER SECOND OF OPERATION

(all values have been divided by 10^{10})

Type of Generator

	Charcoal 2050°F	Propane 1630°F	Propane 1730°F	Acetone Air 1450°F	Acetone Air 1580°F
Temperature of Nuclei Counter -12°C					
	20	64	384	76	160
	100	320	140	265	64
	65	19	80	120	385
	8	170	10	253	130
	47	120	67	400	275
Total	240	693	681	1114	1014
Mean	48.0	138.6	136.2	222.8	202.8
Temperature of Nuclei Counter -15°C					
	192	340	160	1128	1610
	32	128	240	1560	765
	80	96	200	2320	870
	76	560	665	840	580
	145	700	400	325	1800
Total	525	1824	1665	6173	5625
Mean	105.0	364.8	333.0	1234.6	1125.0
Temperature of Nuclei Counter -20°C					
	320	900	1100	3200	2900
	256	2200	600	4800	1600
	375	455	720	1670	5450
	625	345	400	3725	3075
	445	450	1100	2120	1980
Total	2021	4350	3920	15515	15005
Mean	404.2	870.0	784.0	3103.0	3001.0

FIGURE 2

EFFICIENCY OF THE DIFFERENT GENERATORS IN NUMBER OF NUCLEI PRODUCED PER GRAM AGI AT VARIOUS TEMPEATURES

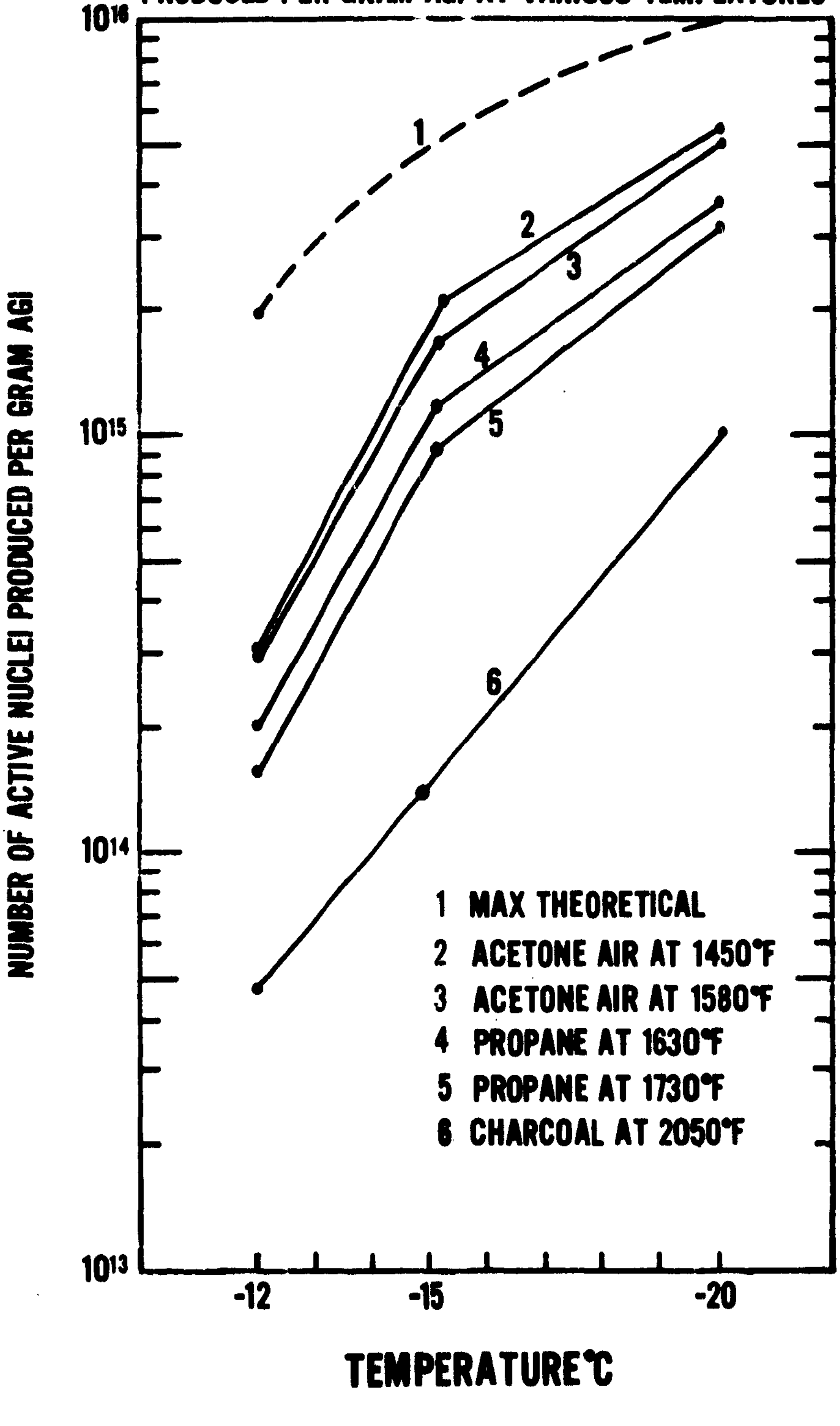


FIGURE 3

EFFICIENCY OF THE DIFFERENT GENERATORS IN NUMBER OF NUCLEI PRODUCED PER SECOND OF OPERATION

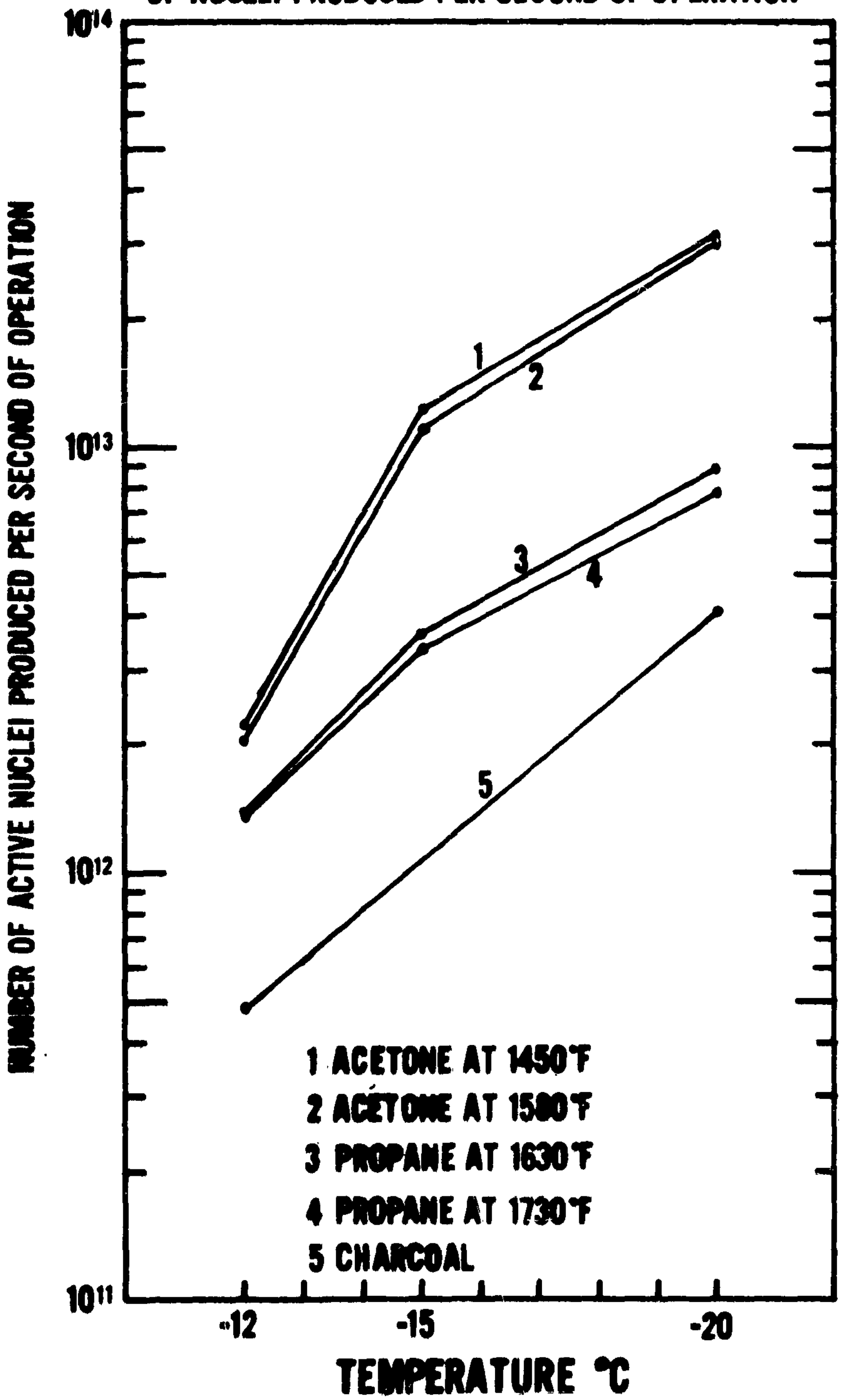
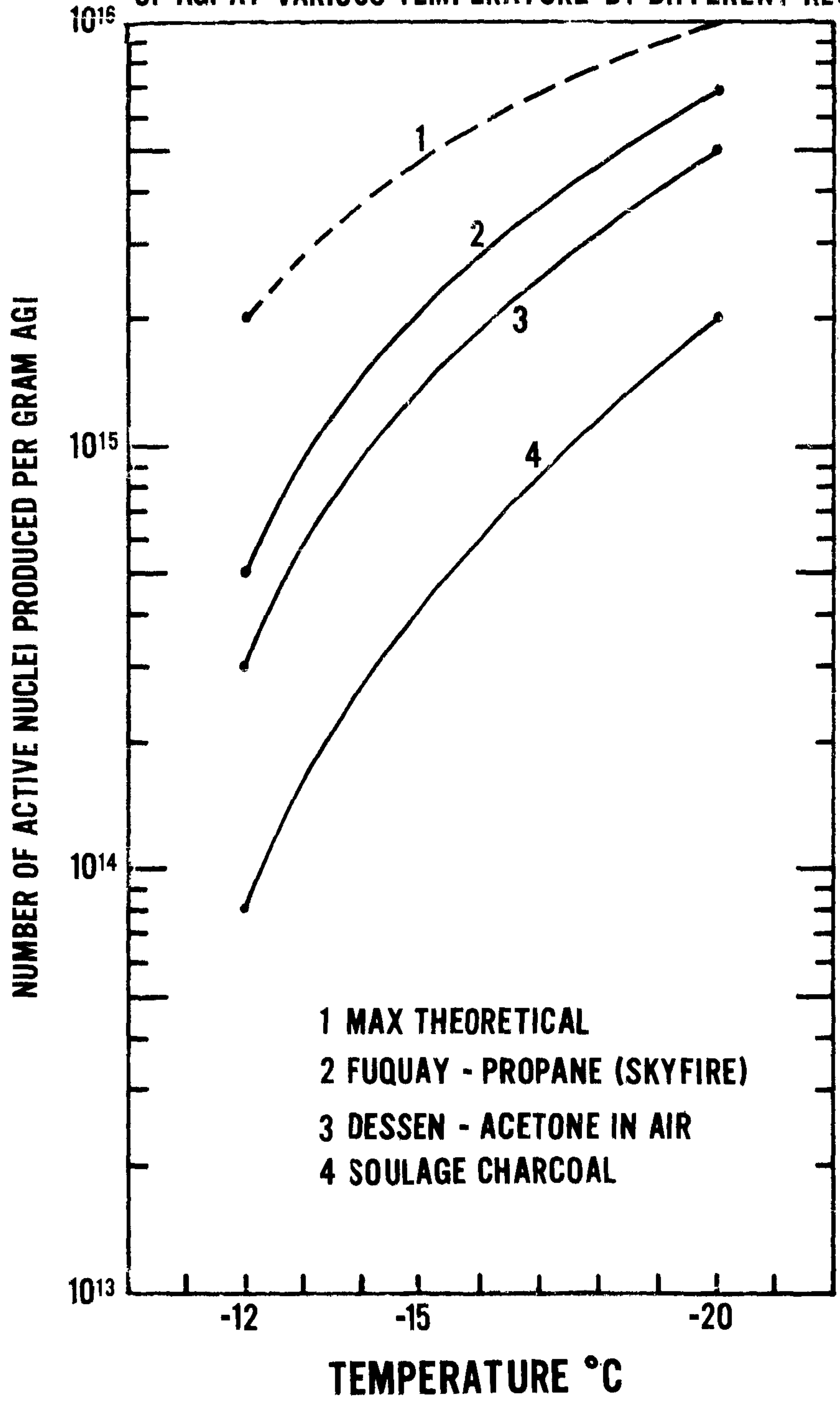


FIGURE 4

EFFICIENCY OF GENERATORS IN NUMBER OF NUCLEI PRODUCED PER GRAM OF AGI AT VARIOUS TEMPERATURE BY DIFFERENT RESEARCHES



average output of the acetone air generator equaled the average output of the charcoal generator. The third tested whether the average output of the propane generator at 1630°F equaled the average output of this generator at 1730°F. The fourth tested whether the average output of the acetone air generator at 1450°F equaled the average output of this generator at 1580°F.

IV. CONCLUSIONS

In general generator efficiency varied with the type of generator and the different temperatures of the ice nuclei counter. The efficiency of the acetone air generator exceeded that of the charcoal generator both in the number of active nuclei produced per gram of silver iodide consumed and in the number of active nuclei produced per second of operation. The acetone air generator proved more efficient than the propane generator in both these aspects. No difference existed between the output of the propane generator at 1630°F and the output of this generator at 1730°F. Likewise no difference appeared between the output of the acetone air generator at 1450°F and the output of the same generator at 1580°F.

The great difference between the number of active nuclei produced by the acetone air generator and the number produced by the charcoal generator supported the theory that the operating temperature of the generator profoundly affects generator efficiency. The average difference in operating temperature between the acetone air generator and the charcoal generator exceeded 500°F, while a difference of only 150°F existed between the acetone air generator and the propane generator. More tests could determine the limit at which lowering the temperature of the generator increases the efficiency of the generator.

A comparison of Figures 2 and 4 shows that the results in terms of the number of nuclei per gram of silver iodide agree very closely with Dessens (3, p.23-40). The fact that the Skyfire Generator used a 4% silver iodide acetone solution while this study used a 2% solution may account for part of the difference between propane generator and the Skyfire Generator (5, p.79-91). The difference between the results found here for the charcoal generator and the results Soulage (12, p.1-8) obtained may stem from the different methods of determining the amount of silver iodide consumed.

V. SUGGESTIONS FOR FURTHER RESEARCH

Since the acetone air generator proved the most efficient, further research efforts concentrated on this generator should result in even greater efficiency. A need exists for a more accurate measurement of the operating temperature of this generator and a determination of the lowest temperature giving maximum efficiency.

The length of exposure of the silver iodide to a given temperature may influence the amount of decomposition of the silver iodide. Studies of this factor should furnish data needed in any final determination of generator efficiency.

Desirable cloud temperatures for cloud modification range close to 0°C. Studies of methods of getting a more accurate nuclei count at these temperatures either with the U. S. Weather Bureau Bigg-Warner Type Ice Nuclei Counter or with some other method of ice nuclei counting would furnish needed data.

Although the ten cubic centimeter syringe functioned satisfactorily in this study, a researcher could more easily use a larger syringe and this would increase the accuracy in any study requiring a greatly diluted sample.

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